Effects of Biomass Removal Treatments on Stand-Level Fire Characteristics in Major Forest Types of the Northern Rocky Mountains

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ABSTRACT

Removal of dead and live biomass from forested stands affects subsequent fuel dynamics and fire potential. The amount of material left onsite after biomass removal operations can influence the intensity and severity of subsequent unplanned wildfires or prescribed burns. We developed a set of biomass removal treatment scenarios and simulated their effects on a number of stands that represent two major forests types of the northern Rocky Mountains: lodgepole and ponderosa pine. The Fire and Fuels Extension to the Forest Vegetation Simulator was used to simulate effects including stand development, fire behavior, and fire effects prior to the biomass removal treatment and 1, 10, 30, and 60 years after the treatment. Analysis of variance was used to determine whether these changes in fuel dynamics and fire potential differed significantly from each other. Results indicated that fire and fuel characteristics varied within and between forest types and depended on the nature of the treatment, as well as time since treatment. Biomass removal decreased fire potential in the short term, but results were mixed over the long term.

Keywords: fire hazard, fuel treatment, whole tree harvest, mastication, fire behavior, fire effects

Biomass may be removed from forest stands to provide lumber, paper products, fuelwood; to manipulate stands to increase their health, resilience, or biodiversity; or to reduce fuel hazard (Patton-Mallory 2008). In many cases there are multiple objectives for stand treatment, and the level of biomass removal that best meets these multiple objectives over time is not always clear. Biomass removal treatments affect the ecosystem in a wide variety of ways (Brown et al. 2003), and because biomass removal treatments are so varied in type and intensity, it is nearly impossible to describe the resultant effects unless the local conditions and details of the treatment design are known.

Management affects biomass at the time of treatment and also subsequent fuel dynamics. Thinning, for example, removes some biomass from the stand and transfers some biomass from the stand canopy to the forest floor, depending on the specifications of the treatment. Fire removes some fuel from the stand in the form of emissions and also moves some biomass from standing live trees to standing dead trees because of fire-caused mortality. These dead trees fall to the forest floor over time, causing increases to the fuels on the forest floor. Removal of dead and live biomass from forested stands can thus influence the intensity and severity of a subsequent unplanned wildfire or a planned prescribed burn (Reinhardt and Ryan 1998, Graham et al. 1999, Fiedler et al. 2004, Graham et al. 2004, Agee and Skinner 2005, Peterson et al. 2005).

Biomass removal treatments, including timber harvests, fuel reduction cuttings, and ecosystem restoration activities, usually involve some sort of tree cutting or harvest activity that may be coupled with postcutting treatments such as prescribed fire. Since biomass removal treatments are diverse and their effects subject to local conditions, there are many ecosystems and treatments that have not received adequate research evaluating effects, and it would be difficult, costly, and resource-intensive to conduct field experiments for all possible combinations of treatments and forest types. Simulation modeling provides a less desirable but more cost-effective alternative for assessing potential effects of biomass removal on fire potential. By linking vegetation dynamics models with fire models that simulate fire behavior and effects, we can compare alternative treatments using metrics that describe fire potential.

This article reports the simulated effects of a suite of biomass removal treatments on the fuel dynamics and fire characteristics of the post-treatment stand over time. We evaluated treatment effects at the stand level on fuel characteristics including canopy bulk density and quantity of duff, standing woody, downed woody, and foliar biomass and fire characteristics including flame length, torching and crowning indices, and tree mortality under severe fire weather conditions. These responses were computed for 60 years using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) system (Reinhardt and Crookston 2003). We discuss the implications of these findings, including (1) importance of monitoring changes as a consequence of biomass removal, (2) guidelines to managers on what activities will result in the most efficient fire-related treatments, and (3) potential analysis techniques for

Manuscript received September 22, 2008; accepted March 18, 2009.

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This article uses metric units; the applicable conversion factors are: kilometers (km): 1 km = 0.6 mi; kilograms per cubic meter (kg/m^3) = 2.2 lb/35.3 ft^3.

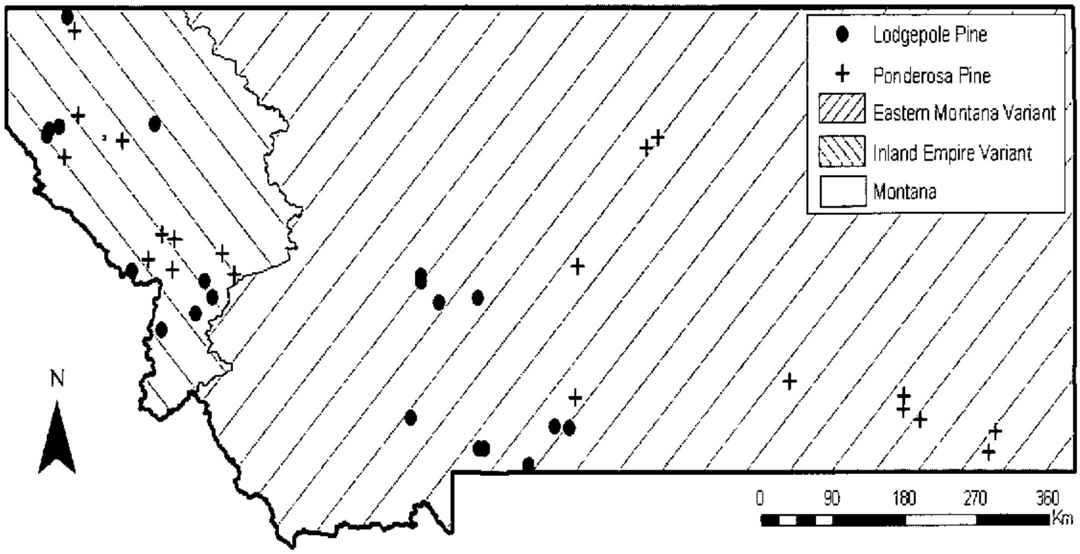

Figure 1. Locations of the 40 sample stands, including lodgepole pine and ponderosa pine, in the Inland Empire Variant (primarily west of the Continental Divide) and the Eastern Montana Variant.

evaluating changes in fire dynamics as a consequence of biomass removal.

Methods

To focus the implementation of this study, we confined our analysis and discussion to fire behavior and effects at the stand level—we did not evaluate landscape and tree-level impacts of biomass removal treatments. We simulated combinations of three harvest treatments, three postharvest treatments, and two burn treatments on 10 stands, representing each of four major forest types. We used the FFE-FVS (Reinhardt and Crookston 2003) for these simulations because it contains a tree growth and regeneration model linked to fire behavior and effects simulation packages. FFE-FVS is a nationally supported tool available to forest managers and is calibrated for most of the United States.

FFE-FVS

The FFE-FVS is a stand-level model that simulates fuel dynamics and potential fire behavior over time, in the context of stand development and management. FFE-FVS links existing models to represent forest stand development (the Forest Vegetation Simulator; Wykoff et al. 1982), fire behavior (Rothermel 1972, Van Wagner 1977, Scott and Reinhardt 2001), and fire effects (Reinhardt et al. 1997). These models are linked together with newly developed models of snag and fuel dynamics. Users can simulate fuel treatments including prescribed fire, wildfire, thinning, and mechanical treatments. Model output includes stand descriptors and predicted fuel loadings over time. If a prescribed fire or wildland fire is simulated, output also includes predicted fire behavior, fuel consumption, smoke production, and tree mortality.

Fuel dynamics are modeled in FFE-FVS using accumulation and decomposition algorithms, as well as transfers between fuel pools: for example, dead standing wood falls to the ground over time and becomes surface woody fuel. Surface woody fuel decomposes over time and a portion of it becomes duff. A portion of the foliage (depending on tree species) falls to the ground each year and becomes litter. The snag and fuel dynamics algorithms contained in FFE-FVS are geographically specific and were developed from literature review and expert opinion (Reinhardt and Crookston 2003).

Data

We selected stands from two major forest types: ponderosa pine (PP) and lodgepole pine (LP), which are among the most commonly harvested types in the northern Rocky Mountain region. These forest types were then divided geographically by east (E) and west (W) side of the Continental Divide to represent different ecoregions. We randomly selected 10 plots to represent each of these four forest/geographic types from the Forest Inventory and Analysis (FIA) database (US Forest Service 2009) (Figure 1). The FIA program has collected stand-level data across the nation using a set of nested plots located along a 5-km grid. We keyed each FIA plot in the northern Rockies to the forest types on the basis of location (east and west of the Continental Divide) and species with majority of basal area (>50% stand basal area of PP and LP). We also restricted plot selections to mature stands (age greater than 80 years) suitable for biomass removal and chose only those plots outside a 50-km buffer of the Continental Divide to ensure geographic distinction between regions.

Simulation and Analysis

The set of biomass treatments designed for this study represent common stand-level treatments used in forest and ecosystem management (Table 1). We modeled three harvest treatments. A commercial thin was included to illustrate changes in fire characteristics under common thinning guidelines; for this study, the trees ≥4 in. dbh and less than an upper limit of 10 in. dbh for lodgepole pine and 20 in. dbh for ponderosa pine were removed with a cutting efficiency of 90%. The ecosystem restoration (ER) treatment was intended to mimic historically common low-intensity surface fire regimes. Ecosystem restoration treatments remove shade-tolerant understory trees to create stand structures that are more characteristic of those with a natural fire regime and increase fire resilience of

Table 1. Details of the treatments used in this study.

Factor	Code	Description
Commercial thinning	CT	Remove all trees (within specified dbh) with cutting efficiency of 0.9: LP: ≥4 and <10 in. dbh PP: ≥4 and <20 in. dbh
Ecosystem restoration	ER	LP: first thin trees up to 4 in. dbh with a 0.9 cutting efficiency and then cut larger trees up to 10 in. dbh until a basal area of 60 ft^2/acre is attained, preferentially selecting subalpine fir and then other species; PP: first thin trees up to 4 in. dbh with a 0.9 cutting efficiency and then cut larger trees up to 20 in. dbh until 60 ft^2/acre basal area is attained, preferentially selecting Douglas-fir and then other species
No treatment	NT	No harvest
Whole tree Slash removal	WT	Remove all branches and stems and tops from site
Mastication	M	Branches, stems, and tops less than or equal to inches in diameter are masticated
No treatment	NY	Branches, stems, and tops less than or equal to inches in diameter are scattered on site
Prescribed burning	PB	Conduct a prescribed burn that kills all trees ≤4 in. dbh, reducing total fuels by 40%
No treatment	NB	

LP, lodgepole pine; PP, ponderosa pine.

the residual stands (Brown et al. 2004, Graham et al. 2004, Hardy et al. 2006). Ecosystem restoration treatments may or may not produce commercial material. We simulated the ER treatments by specifying removal of 90% of the trees less than 4 in. dbh, and then continuing to remove successively larger trees up to a residual basal area of 60 ft^2/acre or a residual upper diameter of 10 in. for lodgepole pine or 20 in. for ponderosa pine, whichever came first, preferentially removing shade-tolerant subalpine fir in lodgepole stands and Douglas-fir in ponderosa pine stands. A no-harvest treatment was also included to monitor fuel dynamics, fire behavior, and fire effects without any harvest treatment. All harvest treatments were then assigned a secondary postharvest slash treatment: (1) whole tree yarding, (2) mastication, or (3) no slash treatment; and a tertiary burn treatment: (1) prescribed burning or (2) no prescribed burning. Whole tree yarding was simulated by removing all branchwood and tops of harvested trees from the stand. Mastication was simulated as reducing the depth of the fuel bed by 50% to represent the crushing and shredding effects of mastication, which accelerates decomposition and reduces potential fire intensity. The prescribed fire treatment was simulated as a moderate-intensity fire that killed trees less than 4 inches in diameter and consumed 40% of the surface fuel on the site. An option in FFE-FVS allows fires to be simulated that achieve particular effects; the moisture and weather conditions that result in these effects are not specified.

Two classes of response variables were computed. The first class was fuel and stand descriptors: canopy bulk density (kg/m^3), quantity of duff (tons/acre), standing woody biomass (tons/acre), downed woody biomass (tons/acre), and foliar biomass (tons/acre). The second class of response variables were estimates of the potential fire impact should a fire burn through the stand under severe weather conditions. Severe weather conditions were assumed to be 20 mph wind speed, 70°F temperature, 4% moisture of fuels of less than 1 in. diameter, 5% moisture for fuels of 1–3 in. diameter, 10% moisture for ≥3 in. diameter woody fuels, 15% duff moisture and 7% live fuel moisture. Fire response variables were flame length (ft), torching and crowning indices (mph), and stand basal area tree mortality (%).

FFE-FVS simulations were conducted by importing FIA plot data into FFE and implementing the treatment scenarios using FFE commands. Response variables were computed before treatment and again 1, 10, 30, and 60 years post-treatment, as the stands aged and the fuel beds changed dynamically through litter fall and decomposition. These simulations were repeated for all 10 stands in each forest type (two types) and geographic area (east- or west-side), and all treatments (three primary harvest treatments, three secondary fuel treatments, and two tertiary burn treatments), resulting in a total of 720 simulations and 3,600 observations (five points in time).

We performed independent-samples t tests, $P = 0.05$, for equality of means (two-tailed and equal variances assumed) to compare means between treatments in canopy base height, canopy bulk density, torching and crowning indices, and stand basal area mortality under severe wildfire conditions 10 years after treatment using SPSS 13.0 software. We restricted this analysis to the 10-year post-treatment results because simulation results become less reliable as the projection period increases. Simulation results were also analyzed using a full factorial analysis of variance (ANOVA) approach for each forest type, with geography, harvest treatment, postharvest slash treatment, and burn treatment as factors. We used the 10 stands as replicates. This ANOVA design was replicated for each of the 10 response variables at each of the five points in time and for each forest type and geographic variant.

Results

Mean and standard deviation of pretreatment values for the 10 response variables are shown for each forest type and geographic area (Table 2). Standard deviations were large, indicating that even mature stands within a cover type and geographical region vary substantially in their fuel and fire characteristics. Pretreatment differences between lodgepole pine and ponderosa pine stands were large, whereas geographical differences within species type were small.

Immediate effects of the treatments on stand basal area, volume removed, surface fuel consumption by prescribed fire, and residual small and large surface woody fuels are shown in Figures 2 and 3. Commercial thinning reduced the basal area further and removed more volume than ecosystem restoration thinning, especially in the ponderosa pine stands (Figure 2). Lodgepole pine stands tended to have more surface woody material following treatment and also to have more fuel consumed in prescribed burns than ponderosa pine stands. As would be expected, whole tree yarding resulted in lower post-treatment fuel loads than the other treatments (Figure 3).

Contrasting impacts of treatments on potential tree mortality

Table 2. Mean and standard deviation of pretreatment conditions (sampled or initialized by the Fire and Fuels Extension to the Forest Vegetation Simulator) in the 40 stands.

	Ponderosa pine		Lodgepole pine	
	West	East	West	East
Duff (tons/acre)	2.76 ± 1.25	2.37 ± 1.05	12.99 ± 1.28	13.69 ± 1.52
Standing woody biomass (tons/acre)	35.50 ± 16.51	19.45 ± 11.28	52.79 ± 26.92	45.09 ± 22.08
Downed woody biomass (tons/acre)	4.33 ± 1.89	3.78 ± 1.57	15.12 ± 1.57	15.96 ± 1.86
Foliar biomass (tons/acre)	2.05 ± 1.02	1.38 ± 0.78	2.87 ± 0.90	3.51 ± 1.59
Potential tree mortality (percentage of stand basal area)	41.90 ± 33.84	85.00 ± 21.88	74.00 ± 21.11	93.70 ± 12.58
Torching index (miles/hour)	188.38 ± 300.00	19.09 ± 11.33	189.22 ± 235.87	43.35 ± 31.34
Crowning index (miles/hour)	52.09 ± 18.76	55.12 ± 18.80	24.90 ± 4.85	20.92 ± 7.17
Surface flame length (feet)	4.14 ± 2.97	6.82 ± 1.42	3.20 ± 0.51	4.22 ± 1.69
Canopy bulk density (kg/m^3)	0.04 ± 0.02	0.04 ± 0.02	0.09 ± 0.02	0.12 ± 0.05
Canopy bulk density (lbs/ft^3)	0.0025 ± 0.0013	0.0025 ± 0.0013	0.0056 ± 0.0013	0.0075 ± 0.0031

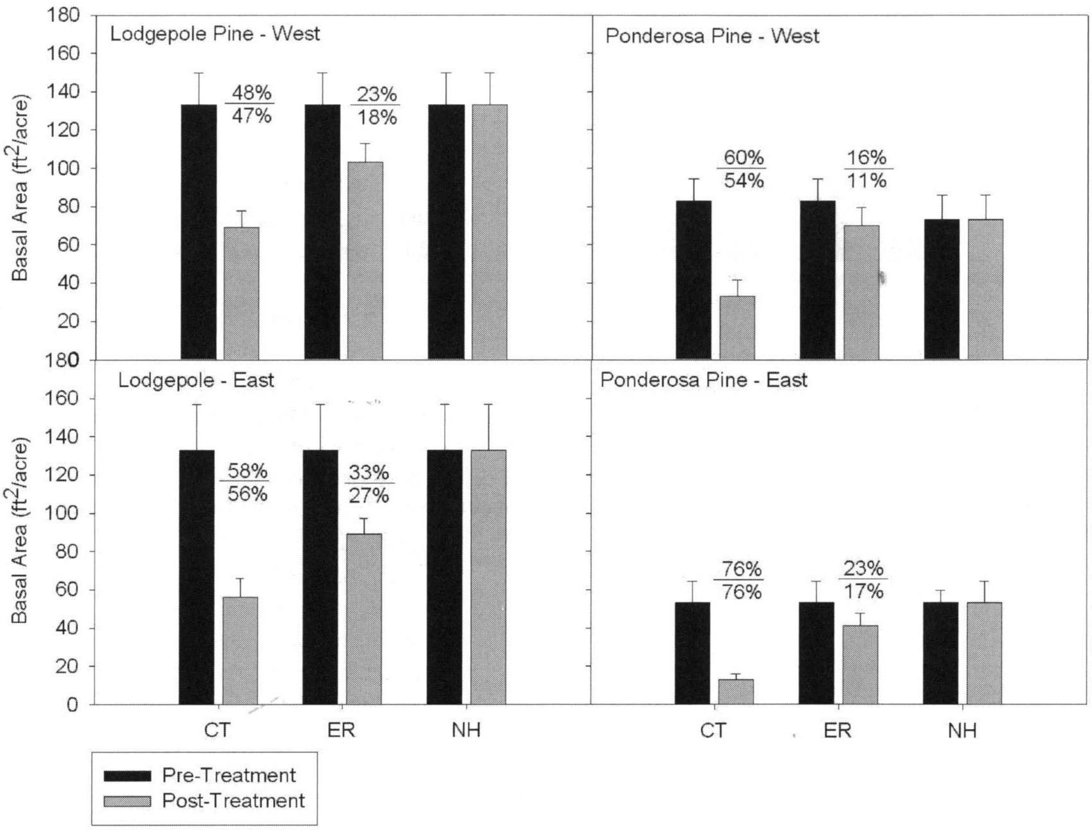

Figure 2. Mean and standard error basal area (ft^2/acre) before (pretreatment), and following (post-treatment) harvest for 10 stands in each forest type (ponderosa pine and lodgepole pine) and geographic area (east and west of the Continental Divide). Values above post-treatment bars represent the percentage of basal area removed (numerator) and percentage of volume removed (denominator). Abbreviations are defined in Table 1.

and canopy bulk density are shown in Figure 4 and 5. After 10 years, potential tree mortality (Figure 4) following wildfire was significantly reduced in most treatments with the exception of commercial thinning with no prescribed fire, which had high potential tree mortality in both east- and west-side ponderosa pine, due probably because activity fuels were generated by the treatment and contributed to potential fire behavior and potential tree mortality. After 60 years, potential tree mortality was still lower than pretreatment for the majority of the treatments, cover types, and geographical areas. In part this is because the stands had grown and trees were naturally more fire resistant. Canopy bulk density was reduced in most instances by the treatment (Figure 5) but had recovered to exceed pretreatment levels by 60 years post-treatment for all except lodgepole pine following the commercial thinning without prescribed fire. The greatest gains in reducing potential tree mortality were for the west-side stands.

Results of the independent-samples t tests comparing 10-year post-treatment effects on crowning and torching index, percentage of basal area tree mortality, canopy base height, and canopy bulk density show that postharvest slash treatment was generally not important (Table 3); these results are illustrated for the mastication treatment. In general, commercial thinning followed by prescribed burning reduced fire potential more than other treatments in both east- and west-side lodgepole and ponderosa pine.

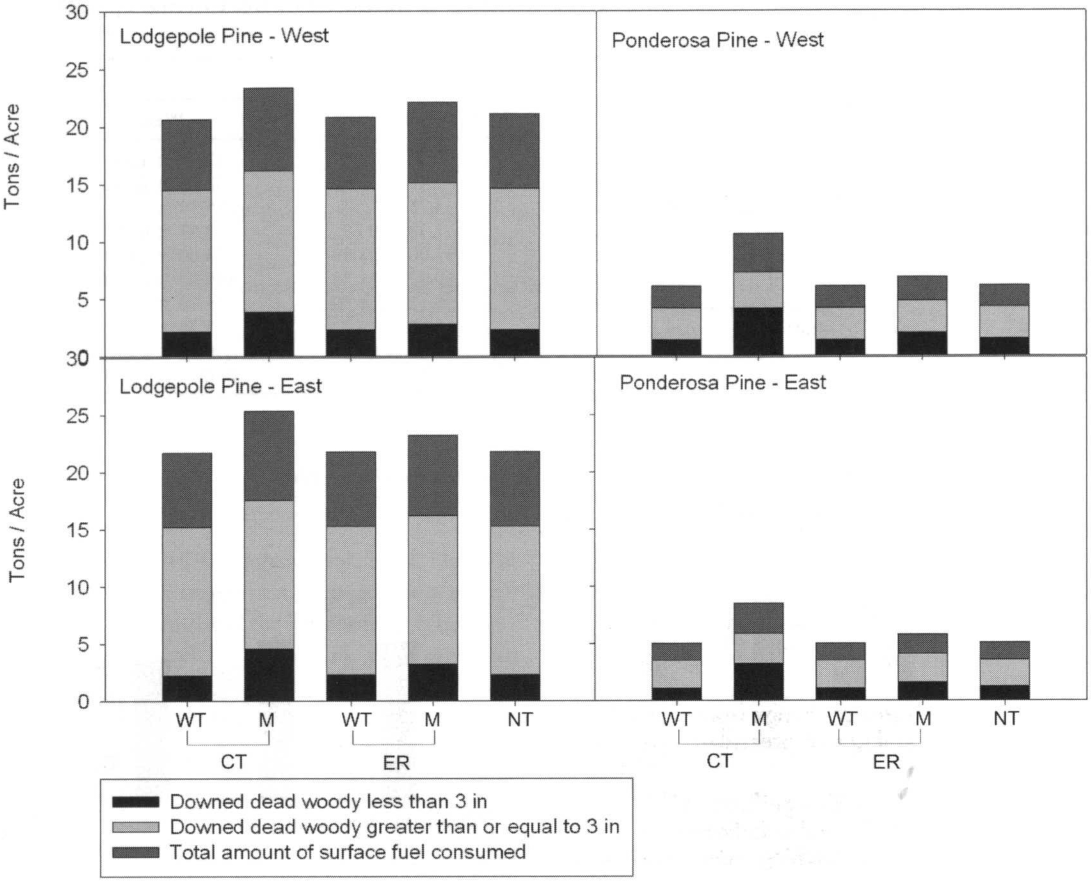

Figure 3. Fuel remaining on the ground following treatments averaged across 10 stands each for ponderosa and lodgepole pine forest types, east and west of the Continental Divide, including total amount of surface fuel (tons/acre) consumed in prescribed fire averaged, amount of downed dead woody material with a diameter of less than 3 in. (tons/acre), and amount of downed dead woody material with a diameter of greater than or equal to 3 in. (tons/acre). Abbreviations are defined in Table 1.

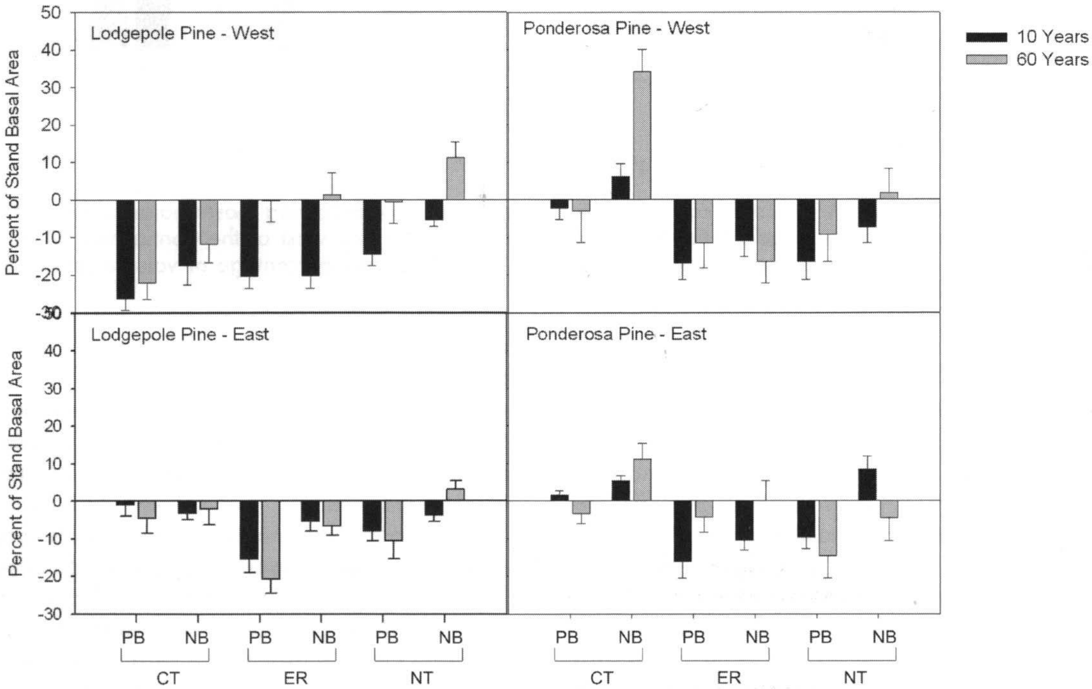

Figure 4. Change from pretreatment levels of potential tree mortality (percentage of stand basal area) 10 and 60 years after treatment for different combinations of thinning and prescribed fire, mean and standard error. Abbreviations are defined in Table 1.

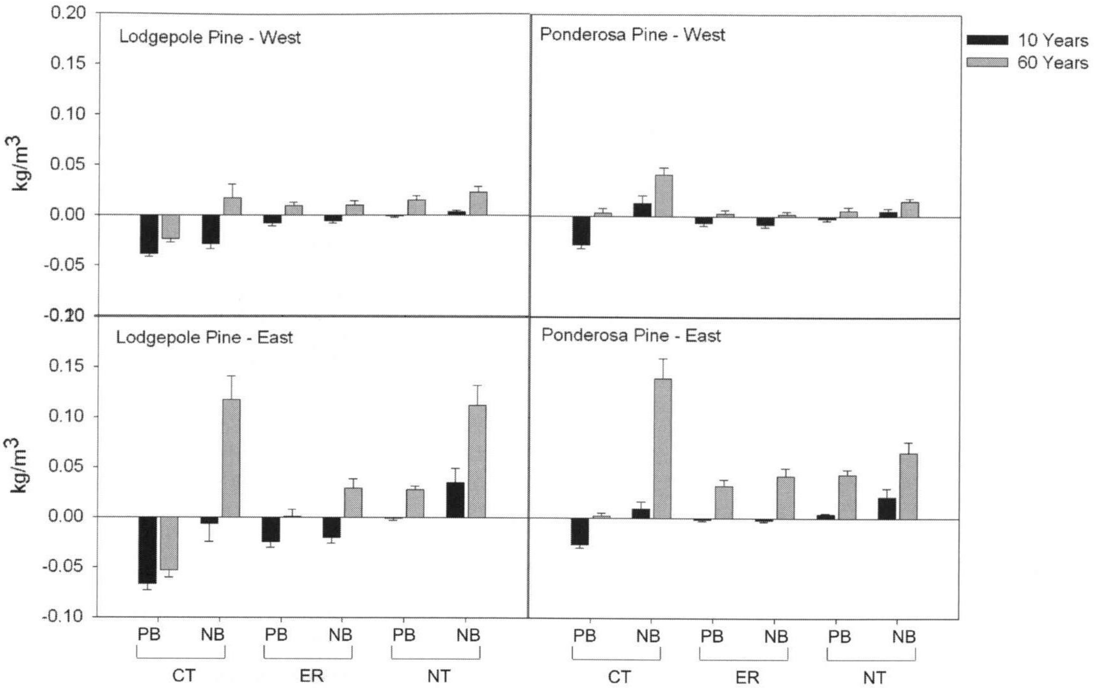

Figure 5. Mean and standard error of change from pretreatment levels of canopy bulk density (kg·m^3) 10 and 60 years after treatment for different combinations of thinning and prescribed fire. Abbreviations are defined in Table 1.

Table 3. Number of fire variables with significant differences ($P < 0.05$) between treatments, estimated for the time period 10 years following treatments, where a positive value indicates reduced fire potential, and a negative value indicates greater fire potential. Fire variables tested were crowning index, torching index, potential mortality as a percentage of basal area, canopy base height, and canopy bulk density.

		Commercial thin		Ecosystem restoration		No harvest	
		No burn	Burn	No burn	Burn	No burn	Burn
Ponderosa pine, west							
Commercial thin	No burn		−2				
	Burn			+2	+2	+2	+2
Ecosystem restoration	No burn					+1	
	Burn						
No harvest	No burn						
	Burn						
Ponderosa pine, east							
Commercial thin	No burn		−4	−1	−1		−1
	Burn			+3	+2	+4	+3
Ecosystem restoration	No burn					+3	
	Burn					+2	
No harvest	No burn						−2
	Burn						
Lodgepole pine, west							
Commercial thin	No burn			+2	+2	+2	+2
	Burn			+2	+2	+4/−1	+2
Ecosystem restoration	No burn						
	Burn						
No harvest	No burn						
	Burn						
Lodgepole pine, east							
Commercial thin	No burn		−2		−1	+1/−1	−2
	Burn			+3	+2/−1	+3/−1	+3/−1
Ecosystem restoration	No burn					+1	−1
	Burn					+3	
No harvest	No burn						−2

Each cell in the table depicts how many of these five variables had significant differences and the direction of difference, with positive values indicating reduced fire potential. For example, a value of + 2/− 1 indicates that two of the five variables had significantly less fire potential in the row treatment than the column treatment, one variable showed significantly greater fire potential, and one had no significant difference.

Results from the ANOVA show that the effects of postharvest fuel treatment diminish over time (Table 4), suggesting that postharvest fuel treatments such as mastication or whole tree yarding become unimportant as early as 10 years post-treatment. Prescribed burning effects, conversely, persisted through the simulation period, as did the harvest treatments.

Table 4. Percentage of 10 fire and fuel variables tested with significant differences ($P < 0.05$) between factors in a factorial analysis of variance.

	Ponderosa	Lodgepole
	(%)	
Pretreatment		
Geography	80	100
Harvest	0	0
Postharvest treatment	0	0
Fire	0	0
1 Year post-treatment		
Geography	80	70
Harvest	70	80
Postharvest treatment	50	50
Fire	40	70
10 Years post-treatment		
Geography	70	90
Harvest	70	80
Postharvest treatment	10	0
Fire	70	80
30 Years post-treatment		
Geography	70	80
Harvest	80	80
Postharvest treatment	0	0
Fire	80	80
60 Years post-treatment		
Geography	90	90
Harvest	50	90
Postharvest treatment	0	0
Fire	70	80

Discussion

The evaluation of biomass removal alternatives on fire potential is complex and many-faceted. Treatment alternatives cannot be exhaustively evaluated, since there are so many combinations of treatments possible. This study, for instance, evaluated only one harvest intensity for each treatment alternative, rather than considering a range. Similarly, only one burn prescription was assessed, although many different burn prescriptions might have been feasible. The scenarios modeled in this study were designed to represent common land management treatments rather than to represent the entire span of possible treatments. Consequently, there are many treatments that are not represented in our set of scenarios. Managers have an opportunity to fine-tune prescriptions to best treat local conditions and meet particular objectives.

Postharvest slash treatment (mastication, whole tree yarding, or no treatment) were not as important as harvest and prescribed fire treatments over time. This may be because the slash treatments affected the surface fuels only and not the subsequent development of the stand. Thinning and prescribed fire, which change stand structure and composition, have much more lasting effects on fuels and fire potential.

Treatments can alter many aspects of a stand and thus of fire potential. In this study, we chose 10 indicators of fire potential, including descriptors of fuel and potential fire behavior and effects. Only one weather scenario was selected to assess fire potential; any number of weather conditions might actually occur. We evaluated the treatments at a small number of time points after treatment. In fact, fuels and fire potential change dynamically and continuously—and not always consistently. The relative success of treatments in reducing fire potential may change as stands and fuels develop.

Results varied substantially by stand even though stands were chosen to be mature and of a given cover type and geographic area. This suggests the need to assess fire hazard and potential and develop treatment options at the stand level, rather than making general recommendations for a forest type as a whole. The FIA data that we used contained inventory data for the stands but not for surface fuels. Surface fuels were estimated at the beginning of the simulation by algorithms in FFE-FVS based on canopy closure and cover type. However, surface fuels tend to be extremely variable and not well correlated to these variables, and fire behavior is strongly driven by surface fuels. Brown and See (1981) analyzed fuel data from thousands of plots in the northern Rocky Mountains and found that "very little of the observed variation in loading was explained by any of the factors" they examined. These factors included stand age, aspect, slope, elevation, habitat type, and cover type. Therefore, our analysis would have been much more robust if surface fuels had been inventoried at the time stands were sampled.

FFE-FVS provides a number of metrics for assessing fire potential. These include characteristics of the stand and fuels such as canopy bulk density, canopy base height, and surface fuel loading. Potential fire behavior is also calculated under a predefined set of weather conditions to give measures of fire hazard such as potential flame length, torching and crowning indices, and potential stand mortality over the simulation period. The torching and crowning indices take into account surface and canopy fuels to compute the wind speed at which torching and active crown fire behavior might be expected to occur. The index values are these threshold wind speeds; the lower the critical wind speed, the more vulnerable a stand is to crown fire (Scott and Reinhardt 2001). Very high values of the torching or crowning index mean that a stand is unlikely to experience torching or crowning, since such wind speeds are unlikely to occur. Conversely, if the index value is very low, it is relatively likely that a fire occurrence might coincide with winds of at least that magnitude, leading to crown fire behavior.

FFE-FVS is primarily a stand-level model, although it can be run on many stands at once. It does not assess landscape level processes. For example, the effects of fuel treatments on fire at a landscape level cannot be modeled with FFE-FVS alone. FFE-FVS also does not predict or assess within-stand variability.

Management Implications

The results reported here indicate the utility of site-specific analysis to develop effective biomass removal treatments. The outcomes of treatments varied between stands, indicating that cookbook, one-size-fits-all fuel treatment prescriptions are likely to be unsatisfactory. Site-specific analysis can integrate the particular stand structure and fuel characteristics to estimate effects of treatment on fire. FFE-FVS can then be used to design a custom fuel treatment prescription for a particular stand to meet particular objectives.

These results also show the importance of post-treatment monitoring to increase our observations of treatment effects. Simulation results are useful for comparing alternatives, but direct observation of effects can provide us with new knowledge to support better decisionmaking and enhanced stewardship.

Biomass removal in general can be expected to reduce potential fire behavior in the short run, since surface fuels are removed. Simulated effects of thinning and prescribed fire treatments were much more persistent than whole tree yarding or mastication.

In the long run, opening a stand and removing biomass alters stand dynamics and fuel dynamics. Effects on potential fire behavior may vary with time since treatment as well as pretreatment conditions and particulars of the treatment.

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